

# On the non-detection of Glashow resonance in IceCube

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Electron anti-neutrinos at the Glashow resonance (GR, at  $E_{\bar{\nu}_e} \sim 6.3$  PeV) have an enhanced probability to be detected. With three neutrinos detected by IceCube in the (1-2) PeV energy range at present, one would expect that about 1 GR  $\bar{\nu}_e$  should have been detected. The high-energy  $\sim 8.7$  PeV muon neutrino detected by IceCube may not be a GR event. If so, the expected detection number of the GR  $\bar{\nu}_e$  would be  $\sim 90$ , then one would have a “missing Glashow-resonance problem”. This would suggest (1) that  $p\gamma$  interaction rather than  $pp$  interaction is the dominant channel to produce the observed IceCube high-energy neutrinos; (2) that multi-pion  $p\gamma$  interactions are suppressed; and (3) that the magnetic field and photon energy density in the  $p\gamma$  emission region is such that significant  $\mu^+$  cooling occurs before decaying, yet  $\pi^+$ ’s essentially do not cool before decaying.

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*I. Introduction.* — Observations of TeV-PeV neutrino events by the IceCube Neutrino Observatory[1, 2] opened up the window to study the astrophysical origin of high energy neutrinos and their production mechanisms. IceCube detects shower and track events from the deep inelastic scattering of high energy neutrinos off the nucleons in the ice. These high energy neutrinos are produced in the astrophysical environment due to the interaction of high energy cosmic rays with the background gas ( $pp$ ) or radiation ( $p\gamma$ ) to produce pions. The subsequent decay of charged pions and muons would produce high energy neutrinos detected by IceCube.

The interaction cross sections of high energy neutrinos and anti-neutrinos with atomic electrons are very small compared to those of the interactions with nucleons. However, in the resonant scattering of

$$\bar{\nu}_e e^- \rightarrow W^- \rightarrow \text{anything (hadrons + leptons)}, \quad (1)$$

the electron anti-neutrinos of energy

$$E_{\bar{\nu}} \simeq M_W^2/(2m_e) \simeq 6.3 \text{ PeV} \quad (2)$$

have an enhanced probability to interact with the atomic electrons in the ice to produce the on-shell  $W^-$  boson. This is the so called *Glashow resonance* (GR)[3]. The cross section at GR is about 300 times higher than that of the charged current (CC) neutrino-nucleon interaction.

This process is unique and of particular interest because of the dramatic increase in the event rate at the resonance energy. At this energy the  $W^-$  boson will predominantly decay to hadrons (68%). Other channels include  $W^-$  boson decay to three species of charged leptons and their corresponding anti-neutrinos, respectively. Each of the leptonic channel has a branching ratio of  $\sim 11\%$ . So the fraction of the leptonic decay mode which

produces a muon and its associated track-like event is small. On the other hand, the cascade/shower from the hadronic decay is the most promising way of detecting the GR. As the Earth is opaque to very high energy neutrinos, only the downward to horizontal going GR events can be observed by IceCube[4, 5].

The showers due to the decay of resonantly produced W-bosons can have peaks at three different energies depending on its decay channel[6]. The dominant one is at 6.3 PeV which is produced due to hadronic decay of the W-boson. If the W-boson decays to  $e^-$  and  $\bar{\nu}_e$  ( $W^- \rightarrow e^- \bar{\nu}_e$ ), a peak at 3.2 PeV is formed. A third peak can be formed at 1.6 PeV from the  $\tau$  decay mode ( $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ ). The decay to muon will give a track without any peak.

The energy estimate from a cascade event in IceCube is more accurate compared to a muon track. Due to the much higher interaction cross section of the GR process, it is expected to contribute substantially to the event rate in IceCube. This would offer a good chance to detect a signal from electron anti-neutrinos of astrophysical origin, and would provide information about the production mechanisms of high energy neutrinos in the astrophysical sources.

So far IceCube has detected 54 events that might have an astrophysical origin, out of which three events have the highest energy in the range of (1-2) PeV and all of them are shower events[1, 2, 7]. If at all these three PeV events are from the GR, they must be from the leptonic decay mode of the GR[4]. However, there is no convincing reason why such a sub-dominant decay mode is more favorable than the dominant hadronic mode. Most probably, these three PeV events are not from the GR, but are from the charged current or neutral current interactions of the electron and/or tau neutrinos with the

nuclei in ice. An extremely high-energy muon neutrino with energy  $\sim 8.7$  PeV was also reported by the IceCube team[8]. This track event deposited 2.6 PeV energy in the detectors. The probabilities that the primary neutrino was a  $\nu_\mu$ ,  $\nu_\tau$ , and  $\bar{\nu}_e$  are 87.7%, 10.9%, and 1.4%, respectively. Not only the probability of being  $\bar{\nu}_e$  is low, but the inferred energy (8.7 PeV) is also different from the GR energy (6.3 PeV). So this event is also likely not a GR event.

*II. The potential “missing Glashow resonance” problem.* — If the three (1-2) PeV and one 8.6 PeV IceCube neutrinos are not from the GR, in a model-independent way, one may argue that there could be a “missing GR” problem from the IceCube data. This can be manifested as follows. In astrophysical environments, neutrinos are produced via the  $p\gamma$  interactions

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p \pi^0 \rightarrow p \gamma \gamma, \\ n \pi^+ \rightarrow n \mu^+ \nu_\mu \rightarrow n e^+ \nu_e \bar{\nu}_\mu \nu_\mu, \end{cases} \quad (3)$$

$$p + \gamma \rightarrow X \pi^\pm, \quad (4)$$

or  $pp$  interactions

$$\begin{aligned} pp &\rightarrow X \pi^\pm, \\ \pi^+ &\rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu, \\ \pi^- &\rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu. \end{aligned} \quad (5)$$

In all the channels, one would expect that anti-neutrinos contribute to  $\sim 1/2$  of the total neutrino and anti-neutrino flux. Consider vacuum neutrino oscillations that evenly distribute anti-neutrinos in three species, the  $\bar{\nu}_e$  flux is about  $1/6$  of the total neutrino and anti-neutrino flux [9].

Suppose that the three (1-2) PeV neutrinos (with average energy  $\sim 1.4$  PeV) are produced by cosmic protons through the standard  $p\gamma$ ,  $pp$  processes, one may estimate the expected number of 6.3 PeV GR  $\bar{\nu}_e$ 's by IceCube as

$$\begin{aligned} N_{\bar{\nu}_e, 6.3\text{PeV}} &\simeq N_{(1-2)\text{PeV}} \cdot \left(\frac{6.3}{1.4}\right)^{-p} \cdot 300 \cdot 68\% \cdot \frac{1}{6} \\ &\simeq 0.37 N_{(1-2)\text{PeV}} \sim 1, \end{aligned} \quad (6)$$

where  $p \sim 3$  is adopted [10], which is the typical value for cosmic ray spectrum between knee and ankle where multi-PeV neutrinos/anti-neutrinos can be generated. If the 8.3 PeV neutrino is from GR, then it is consistent with the above estimate. However, if it is not from the GR, as suggested by its small probability of being a  $\bar{\nu}_e$  and the different energy from 6.3 PeV, then the expected GR neutrinos would be

$$N_{\bar{\nu}_e, 6.3\text{PeV}} \simeq 1 \cdot \left(\frac{6.3}{8.7}\right)^{-p} \cdot 300 \cdot 68\% \cdot \frac{1}{6} \sim 90. \quad (7)$$

The above estimate raises a possible “missing GR  $\bar{\nu}_e$  problem”, especially if the 8.7 PeV event is not from the GR. Some other models also suggested that at the resonance peak, the event rate of  $pp$ - and  $p\gamma$ - generated

GR  $\bar{\nu}_e$  would be  $\sim 3.2 - 3.5$  per year and  $0.6 - 0.8$  per year, respectively[11], already exceeding the non-detection limit with a large margin.

*III. Constraints on neutrino-emission mechanism and environments with the missing GR  $\bar{\nu}_e$ .* — Due to the large error boxes, the origin of high-energy neutrinos detected by IceCube remain unknown. The proposed neutrino sources include blazars[12], gamma-ray bursts (GRBs) [13], hypernovae[14], intergalactic shocks[15], and starburst galaxies[16], etc. A stringent constraint on the associations of IceCube neutrinos with GRBs has been placed[17], which posed interesting constraints on GRB models[18]. Possible associations of high-energy neutrinos with blazars have been suggested[12, 19], but the case is not conclusive. Furthermore, it is unknown whether the  $p\gamma$  or the  $pp$  interactions are the dominant channel to produce these high-energy neutrinos.

If the “missing GR  $\bar{\nu}_e$  problem” indeed exists, interesting constraints can be placed on the neutrino-generation mechanisms. In order to suppress the  $\bar{\nu}_e$  flux, one may draw three conclusions: (1)  $p\gamma$  rather than  $pp$  is the dominant channel to produce high-energy neutrinos; (2)  $p\gamma$  interactions proceed in the  $\Delta^+$ -resonance channel, with the multi-pion channels suppressed; (3) the magnetic field and photon energy densities in the  $p\gamma$  emission region is such that significant  $\mu^+$  cooling occurs before decaying, yet  $\pi^+$ 's essentially do not cool before decaying.

The required  $p\gamma$  dominance can be readily seen from Eqs.(3 – 5). The main difference is that  $p\gamma$  produces  $\pi^+$  only at  $\Delta^+$ -resonance, while both multi-pion  $p\gamma$  and  $pp$  processes produce both  $\pi^+$  and  $\pi^-$  [20–22]. When  $\pi^+$  decays, it produces  $\mu^+$  and  $\nu_\mu$ . No significant anti-neutrinos can be produced before  $\mu^+$  decays. For  $\pi^-$ ,  $\mu^-$  and  $\bar{\nu}_\mu$  are produced immediately after  $\pi^-$  decay, so that some  $\bar{\nu}_e$ 's would reach IceCube due to vacuum oscillation as  $\bar{\nu}_\mu$  propagates towards Earth. Of course, when muons decay, anti-neutrinos would in any case be produced. In the rest frame, pions and muons have decay time scales

$$\tau_\pi^0 \simeq 2.6 \times 10^{-8} \text{ s} \quad (8)$$

and

$$\tau_\mu^0 \simeq 2.2 \times 10^{-6} \text{ s}, \quad (9)$$

respectively. Since the muon lifetime is much longer than the pion lifetime, it is possible to suppress high-energy anti-neutrino flux through muon cooling. This is relevant only for  $p\gamma$  interactions at  $\Delta^+$ -resonance. As a result, one may draw the conclusion that  $p\gamma$  is the dominant channel to produce the neutrinos detected by IceCube if one indeed has the “missing GR  $\bar{\nu}_e$  problem”.

Next, for  $p\gamma$  interactions, one needs the multi-pion channel (Eq.(4)). The  $p\gamma$  interactions have a peak at the  $\Delta^+$  resonance but a moderate drop at higher photon energies, where multi-pion processes operate. To suppress multi-pion  $p\gamma$  interactions, one would require a soft target photon spectrum with rapid drop of photon flux at high energies. This is consistent with most models that

invoke a synchrotron seed photon field as the targets, but disfavors the models invoke a thermal photon seeds, such as the choked jet models for GRBs[13]. This is consistent with the non-detection of neutrinos associated with GRBs[17].

Finally, for  $p\gamma$  interactions, one needs to produce several (1-2) PeV neutrinos but suppress  $\sim 6.3$  PeV anti-neutrinos. One may argue that there might be an intrinsic cutoff in the injected cosmic-ray spectrum in this energy range, as is expected in some models[13]. However, the detection of the 8.7 PeV event (likely  $\nu_\mu$ , which can be directly produced via  $\pi^+$  decay) disfavors such a possibility (again assuming that the event is not due GR). One is therefore left with the following possibility, i.e.

$$t_{\pi,c} > \tau_\pi \quad \text{for 2 PeV neutrinos,} \quad (10)$$

$$t_{\mu,c} < \tau_\mu \quad \text{for 6.3 PeV neutrinos,} \quad (11)$$

where  $t_{i,c}$  is the cooling time scale and  $\tau_i = \gamma_i \tau_i^0$  is the lifetime of the species  $i$  (for  $\tau^\pm$  and  $\mu^\pm$ , respectively).

In general, the energy loss rate of a high energy particle with Lorentz factor  $\gamma_i$  (and corresponding dimensionless speed  $\beta_i$ ) reads

$$|\dot{E}_i| = \frac{4}{3} \sigma_{T,i} c \beta_i^2 \gamma_i^2 U_T, \quad (12)$$

where  $i = \pi^\pm, \mu^\pm$  and  $\sigma_{T,i}$  is the Thomson scattering cross section for particle  $i$ , which can be calculated from  $\sigma_{T,i} = (m_e/m_i)^2 \sigma_T$ , with  $\sigma_T \simeq 6.65 \times 10^{-25} \text{ cm}^2$  being the Thomson cross section for electrons. Since the particles are relativistic, one has  $\beta_i \simeq 1$  and  $\gamma_i = E_i/m_i c^2$ . Considering both synchrotron and inverse Compton cooling, the total energy density in the emission region is defined by

$$U_T = U_B + U_{ph} = \frac{B^2}{8\pi} (1 + Y) + U_{E,ph}, \quad (13)$$

where  $B$  is the magnetic field strength in the emission region,  $Y \sim 1$  is the Compton parameter for synchrotron self-Compton (SSC) process, and  $U_{E,ph}$  is the external photon energy density in the emission region. The radiative cooling time for the particle  $i$  is given by

$$t_{i,c} = \frac{E_i}{|\dot{E}_i|} = \frac{3}{4} \frac{m_i c}{\gamma_i \sigma_{T,i} U_T}. \quad (14)$$

In a photohadronic process, the pion carries approximately 20% of the UHE proton energy, whereas, in the pion decay  $\pi^\pm \rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu)$  the muon carries about 75% of the pion energy. In the decay of the charged pion to leptons, each lepton carries about 25% of the pion energy. So in a photohadronic process about 5% of the proton energy is taken away by a single neutrino. If a GR event with 6.3 PeV energy  $\bar{\nu}_e$  is observed in IceCube from the photohadronic process, it corresponds to a parent UHE proton energy  $E_p \simeq 127$  PeV, pion energy  $E_\pi \simeq 25$  PeV and muon energy  $E_\mu \simeq 19$  PeV respectively. Given  $m_\pi \sim 139.57$  MeV, and  $m_\mu \sim 105.66$  MeV,

the estimated Lorentz factors of pions and muons are  $\gamma_\pi \simeq \gamma_\mu \simeq 1.8 \times 10^8$ . To be able to produce a 2 PeV  $\nu_\mu$  from  $\pi^+$  decay, the required pion Lorentz factor is  $\gamma_\pi \simeq 5.7 \times 10^7$ .

The conditions (10) and (11) then lead to a constraint on the total energy density

$$\frac{3}{4} \frac{m_\mu c}{\gamma_\mu^2 \sigma_{T,\mu} \tau_\mu^0} < U_T < \frac{3}{4} \frac{m_\pi c}{\gamma_\pi^2 \sigma_{T,\pi} \tau_\pi^0}, \quad (15)$$

where  $\gamma_\mu \simeq 1.8 \times 10^8$ ,  $\gamma_\pi \simeq 5.7 \times 10^7$ . This gives

$$3.8 \times 10^3 \text{ erg/cm}^3 < U_T < 7.3 \times 10^6 \text{ erg/cm}^3. \quad (16)$$

In the case of synchrotron cooling dominated sources so that  $U_T \simeq U_B = B^2/8\pi$ , this condition can be expressed as a constraint on the magnetic field strength in the source

$$310 \text{ G} < B < 1.4 \times 10^4 \text{ G}. \quad (17)$$

These constraints have important implications on the astrophysical sources of high-energy neutrinos. The co-moving frame magnetic field strength of a relativistic jet with wind luminosity  $L$ , bulk Lorentz factor  $\Gamma$ , and magnetic fraction parameter  $\epsilon_B = L_B/L < 1$  can be estimated as

$$B' = \left( \frac{2\epsilon_B L}{\Gamma^2 r^2 c} \right)^{1/2} \simeq (2.6 \times 10^4 \text{ G}) L_{52}^{1/2} \epsilon_B^{1/2} \Gamma_{2.5}^{-1} r_{14}^{-1} \quad (18)$$

$$\simeq (8.2 \times 10^2 \text{ G}) L_{48}^{1/2} \epsilon_B^{1/2} \Gamma_1^{-1} r_{15}^{-1}, \quad (19)$$

where the convention  $Q = 10^n Q_n$  in cgs units and the characteristic parameters for GRBs and blazars have been adopted. One can immediately see that a GRB internal shock environment roughly satisfies this constraint. However, since so far no IceCube neutrinos have been detected to be associated with GRBs[17], it suggests that successful GRBs are not likely the dominant sources for the IceCube neutrinos. For blazars, in order to satisfy the constraint, one needs to reduce the emission radius to  $r \sim 10^{15}$  cm, which is about 100 times of the BH Schwarzschild radius, suggesting a core origin of neutrinos. Alternatively, one may have a large emission radius, but the neutrino emission region should be permeated with external photons with energy density satisfying the constraint (16). Most other high-energy neutrino models (hypernova or intergalactic shocks) [14, 15] typically have a much weaker magnetic field strength in the emission region. These models would work only when the constraint (16) is satisfied via an in-situ photon background.

*Conclusions.* — We argue that with the current data, there might be a “missing GR problem”. The case is only marginal if the 8.7 PeV neutrino detected by IceCube is a GR event, the probability of which is low. If this event is not a GR, then the missing GR problem is very severe, and some interesting constraints on the origin of

IceCube high-energy neutrinos can be placed. The neutrino production mechanism is likely  $p\gamma$  rather than  $pp$ . For  $p\gamma$  processes, the interactions should mostly proceed at the  $\Delta^+$ -resonance, with the multi-pion interactions suppressed. Also, the neutrino emission site should have a significant amount of magnetic field or photon energy density so that  $\mu^+$  can significantly cool before decaying and producing anti-neutrinos. In the meantime, the energy density should not be too high to cool  $\pi^+$ , so that

2 PeV neutrinos can be generated. This condition places an interesting constraint (Eq.(16)) that any high-energy neutrino model has to satisfy.

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- [21] In the  $pp$  and  $p\gamma$  interactions, besides neutrinos, free neutrons are also produced. Additional  $\bar{\nu}_e$  may be produced from the beta decay process  $n \rightarrow p e^- \bar{\nu}_e$ , either inside or outside the source environment depending on the neutron energy. For such decay, the  $\bar{\nu}_e$  carries  $\sim 10^{-3}$  times the parent neutron energy. So to produce  $\bar{\nu}_e$  with energy in the PeV range, the original proton energy has to be in the EeV range. In most of the astrophysical sources, the neutrino flux drops rapidly with increasing energy. So in

the EeV energy range the cosmic ray flux will be small and hence the neutrino flux.

- [22] The predicted neutrino spectrum from  $pp$  and  $p\gamma$  interactions agrees well with the measurements for neutrinos up to the energy above  $\sim 10^5$  GeV. At higher energies, the charmed hadrons  $D^\pm$ ,  $D^0$  are produced from  $pp$  interaction processes and the neutrino flux from the charm decay known as the *prompt flux* would dominate over the conventional flux. Equal number of neutrinos and anti-

neutrinos of electron and muon flavors are produced in this process and the tau neutrinos and anti-neutrino production is suppressed. The short lifetime ( $\sim 1.0 \times 10^{-12}$  s) of charmed mesons makes them decay before they interact. Also due to large masses of these mesons the radiative cooling is very much suppressed. For the  $p\gamma$  process as we focus on, the prompt flux does not play any role.